APPENDIX F

MINNESOTA STORMWATER MANUAL, CHAPTER 8

(MPCA, September 2006)

Chapter 8: Hydrologic, Hydraulic, and Water Quality Evaluation Methods and Models

An overview of computer models most frequently used to analyze the hydrology, hydraulics, and water quality factors for best management practices. It also includes recommendations for model input parameters.

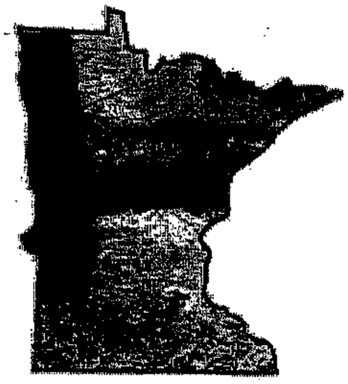


Table of Contents

1. Introduction

1.1 Purpose of Stormwater Modeling

The foundation of stormwater management is an understanding of how a particular land area and drainage system can affect, and can be affected by, the stormwater passing through it. In particular, when (or preferably before) alterations are made to the land area or drainage network, stormwater managers need to understand and anticipate how the alteration is likely to affect the volume, flow rate, and quality of runoff moving through the system, and in turn, how the stormwater is likely to impact the people, property, and natural resources of the area. Modeling is a tool that can be used to understand and evaluate complex processes.

Some kind of stormwater model is needed whenever an estimate of the expected volume, rate, or quality of stormwater is desired. Modeling is also often necessary for the design of BMPs and hydraulic structures and for evaluation of the effectiveness of water quality treatment by BMPs. If monitoring data exists for the specific combination of precipitation and site conditions under consideration, modeling may not be necessary. However, in many cases the conditions to be analyzed do not fit precisely with the conditions monitored in the past and modeling will be necessary.

In general, there are two types of models: physical and numerical. A physical model is a constructed replica of the system whereas a numerical model is based on equations that approximate the processes occurring in the system. Typically, it is not realistic to construct a physical model that would provide reliable hydrologic predictions for a watershed or drainage system, so numerical (nearly always computer-based) models are the standard tool for stormwater management.

Note that this Manual cannot possibly contain a thorough analysis of modeling. Instead, the purpose of this chapter is to introduce a stormwater manager to the terms of modeling and some cursory assessment of model calibration. Those interested in model details are encouraged to follow the links in Appendix B or to locate model manuals.

In practice, stormwater models are most commonly used either as planning and decision making aids for water management authorities, or as tools for developers who wish to design for and demonstrate compliance with regulations and principles governing protection of water and waterways. They are used, for example, to predict:

- Water quality effects of various land management scenarios
- Effects of water control structures on water surface elevations in a channel
- Performance of stormwater management structures such as ponds, wetlands, trenches, etc.
- Wetland impacts resulting from channel excavation
- Lateral extents of a floodplain along a channel

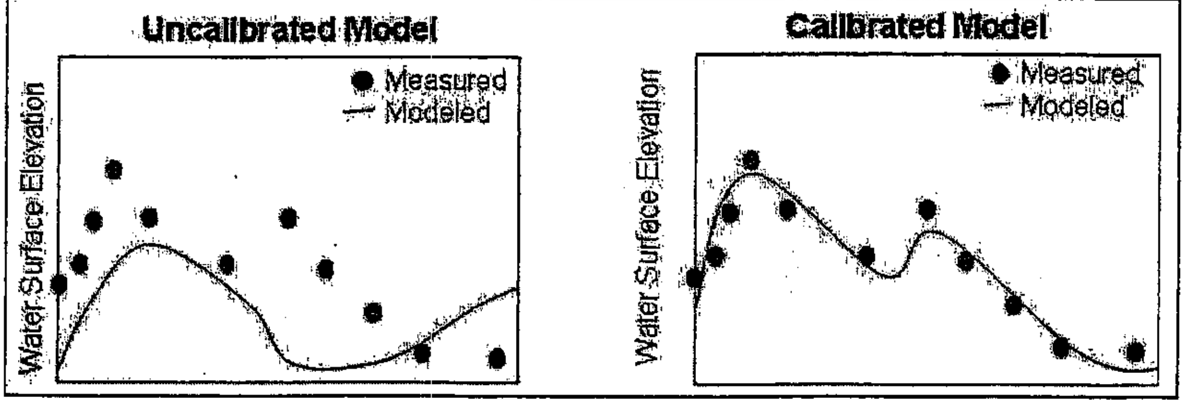
These examples show some of the potential uses of modeling, but the list is by no means exhaustive. Modeling in general is a versatile tool that can be applied to any number of situations.

1.2 Types of Models

The most commonly used stormwater models can generally be classified as either hydrologic, hydraulic, or water quality models.

- Hydrologic models are used to estimate runoff volumes, peak flows, and the temporal distribution of runoff at a particular location resulting from a given precipitation record or event. Essentially, hydrologic models are used to predict how the site topography, soil characteristics, and land cover will cause runoff either to flow relatively unhindered through the system to a point of interest, or to be delayed or retained somewhere upstream. Many hydrologic models also include relatively simple procedures to route runoff hydrographs through storage areas or channels, and to combine hydrographs from multiple watersheds.
- Hydraulic models are used to predict the water surface elevations, energy grade lines, flow rates, velocities, and other flow characteristics throughout a drainage network that result from a given runoff hydrograph or steady flow input. Generally, the output (runoff) from a hydrologic model is used in one way or another as the input to a hydraulic model. The hydraulic model then uses various computational routines to route the runoff through the drainage network, which may include channels, pipes, control structures, and storage areas.
- Combined hydraulic and hydrologic models provide the functions of both hydraulic models and hydrologic models in one framework. A combined model takes the results from the hydrologic portion of the model and routes it through the hydraulic portion of the model to provide the desired estimates.

Figure 8.1 Importance of Model Calibration



Water quality models are used to evaluate the effectiveness of a BMP, simulate water quality conditions in a lake, stream, or wetland, and to estimate the loadings to water bodies. Often the goal is to evaluate how some external factor (such as a change in land use or land cover, the use of best management practices, or a change in lake internal loading) will affect water quality. Parameters that are frequently modeled include total phosphorus, total suspended solids, and dissolved oxygen.

1.3 Limitations of Modeling and the Importance of Calibration

Hydrologic, hydraulic, and water quality models are not exact simulations of the processes occurring in nature. Rather, they are approximate representations of natural processes based on a set of equations simplifying the system and making use of estimated or measured data. The accuracy of a model, therefore, is limited by the quality of the simplifications made to approximate the system processes and the quality of the input data. In some cases, the impact of these limitations can be reduced by using a more complex model or paying to acquire more or better input data. However, it is also important to recognize that oftentimes, it is simply not possible to significantly increase accuracy with such means, because the necessary computational and data collection technology does not exist, and in any case the climatic forces driving the simulation can only be roughly predicted. There also could be time and funding constraints.

Recognizing the high degree of error or uncertainty inherent in many aspects of stormwater modeling can help to focus efforts where they do the most good. Generally, the goal of stormwater modeling is to provide a reasonable prediction of the way a system will respond to a given set of conditions. The modeling goal may be to precisely predict this response or to compare the relative difference in response between a number of scenarios. The best way to verify that a model fulfills this need (to the required degree of accuracy) is to check it against actual monitoring data or observations (Figure 8.1).

The process of model calibration involves changing the estimated input variables so that the output variables match well with observed results under similar conditions. The process of checking the model against actual data can vary greatly in complexity, depending on the confidence needed and the amount of data available. In some cases, the only feasible or necessary action may be a simple "reality check," using one or two data points to verify that the model is at least providing results that fall within the proper range. In other cases, it may be necessary to perform a detailed model calibration, to ensure the highest possible accuracy for the output data. For some models, calibration is unnecessary due to the design of the model.

Calibration should not result in the use of model parameters that are outside a reasonable range. Additionally, models should not be calibrated to fit so tightly with observed data that the model loses its flexibility to make estimates under other climatic conditions.

2. Selecting a Stormwater Modeling Tool

Hydrologic, hydraulic, and water quality models all have different purposes and will provide different information. Table 8.1 summarizes some of the commonly used modeling software and modeling techniques and the main purpose for which they were developed. The table shows the relative levels of complexity of necessary input data, indicates whether the model can complete a continuous analysis or is event based, and lists whether the model is in the public domain. For hydraulic models, Table 8.1 indicates whether unsteady flow calculations can be conducted. For water quality models, the table indicates whether the model is a receiving waters model, a loading model, or a BMP analysis model.

The selection of a stormwater modeling tool is based on the modeling objectives and on the available resources. When evaluating the modeling objectives, the modeler should consider:

- The type of information desired from the modeling effort.
- The specific conditions to be modeled.
- The required level of accuracy and reliability of the model.
- The further use of the model and model results.

For example, estimating peak runoff rates is a different problem than estimating the peak elevation of a water body and could require the use of a different model. A model able to estimate phosphorus loading from a network of detention ponds may not be able to model the phosphorus loading from an infiltration pond.

When evaluating the resources available, the modeler should consider:

- The general limitations of modeling which include imperfect approximations of natural processes, uncertainty and variability in results, and uncertainty and error in the input parameters.
- Availability of existing models used for site analysis.
- Familiarity with the specific model.
- Modeling expertise available.

3. Minnesota Model Input Guide

Chapter 10, Unified Stormwater System Sizing Criteria, outlines recommendations for sizing best management practices. The following sources of information will allow designers to use the above referenced models for estimating hydrologic, hydraulic, or water quality parameters.

3.1 Data Resources

3.1.1. Precipitation

The most commonly referenced precipitation frequency study in Minnesota is the U.S. Weather Bureau's 1961 Technical Publication 40 (TP-40, Hershfield, 1961). Despite potential doubts regarding the adequacy of TP-40, which is viewed by some as outdated and not reflective of recent climate trends, use of newer studies has not taken hold. As a result, TP-40 remains the dominant source for Minnesota precipitation magnitude and return frequency (see also Issue Paper B in Appendix J).

Isopluvial maps showing precipitation depths corresponding to the following 24-hour return events over the entire state are included in TP-40 and reproduced in Appendix B of this Manual:

- 1-year design storm
- 2-year design storm
- 5-year design storm
- 10-year design storm
- 25-year design storm
- 100-year design storm

Design engineers typically make use of precipitation excedence probability to calculate the risks of design failure for channel protection, over-bank flooding, and extreme flooding. A storm magnitude of a return period (T) has the probability of being equaled or exceeded in any given year is equal to 1/T. For example a "100-year" event at a given location has a chance of 1/100 or 0.01 or 1% of being equaled or exceeded in any given year.

Table 8.1 Modeling Tool Selection

Model or Tool*	Input Complexity	Continuous Modeling	Public Domain	Unsteady Flow	Type of Water Quality Model
Rainfall-Runoff Calculation Tools	*peak flow, runoff volume, and/or event hydrograph calculations only*				
TR-55 (original or DOS)	Low	No	Yes	--	--
Rational Method (equation)	Low	No	Yes	--	--
Hydrologic Models	*rainfall-runoff simulation, reservoir & channel routing*				
HEC-1	Medium	No	Yes	--	--
HEC-HMS	Medium	Yes	Yes	--	--
WinTR-20 (or TR-20)	Medium	No	Yes	--	--
WinTR-55	Low	No	Yes	--	--
HydroCAD	Medium	No	No	--	--
Hydraulic Models	*water surface profile determination along waterways & through structures*				
HEC-RAS	Medium	Yes	Yes	Yes	--
HEC-2	Medium	No	Yes	No	--
WSPRO	Medium	No	Yes	No	--
CULVERTMASTER	Low	No	No	No	--
FLOWMASTER	Low	No	No	No	--
Combined Hydraulic & Hydrologic Models	*rainfall-runoff results automatically input into hydraulic calculation module*				
PondPack	Medium	No	No	No	--
EPA-SWMM	Medium / High	Yes	Yes	Yes	--
XP-, PC-, MIKE- SWMM	Medium / High	Yes	No	Yes	--
Water Quality Models					
SLAMM	Medium	Yes	No	--	Loading
P8	Medium	Yes	Yes	--	BMP, Loading
BASINS **					
QUAL2E/QUAL2K	Medium	No	Yes	--	Receiving Waters
WinHSPF	High	Yes	Yes	--	Receiving Waters
SWAT	Medium / High	Yes / No	Yes	--	Loading
PLOAD	Low	No	Yes	--	Loading
PondNet	Low	No	Yes	--	BMP, Loading
WiLMS	Low	No	Yes	--	Receiving Waters
Bathtub	Medium	No	Yes	--	Receiving Waters
WASP	High	Yes	Yes	--	Receiving Waters
EPA-SWMM	Medium / High	Yes	Yes	--	Loading
XP-SWMM	Medium / High	Yes	No	--	Loading

*Further information on each of the above models is available in Appendix B

** BASINS is a group of models, with each of the model having different characteristics

The complete TP-40 document is available on line through the National Weather Service Web site at: www.nws.noaa.gov/ohd/hdsc/temp_currentpf.htm#TP40.

More recent work by others to update, test and/or validate the TP-40 findings include precipitation frequency studies conducted by the Midwest Climate Center (Huff and Angels' 1992 Bulletin 71), Metropolitan Council's Precipitation Frequency Analysis for the Twin Cities Metropolitan Area (study updates in 1984, 1989, and 1995), and Mn/DOT's November 1998 study (Intensity of Extreme Rainfall over Minnesota) in coordination with Richard Skaggs from the University of Minnesota.

In addition to the frequency analysis studies, an impressive source of historical (and current) precipitation data and other climate data for Minnesota exists at the Minnesota Climatology Working Group Web site at: http://www.climate.umn.edu.

3.1.2. Climate Trends

According to Dr. Mark Seeley, University of Minnesota, sufficient data exist to support recently observed trends of climate change in Minnesota. Notable changes over the last 30 years include:

- Warmer winters.
- Higher minimum temperatures.
- Increased frequency of tropical dew points.
- Greater annual precipitation with:
    - More snowfall.
    - More frequent heavy rainstorm events.
    - More days with rain.

The increasing precipitation and snowfall trends suggest the need for an updated Minnesota precipitation study.

3.1.3. Topographic Data

General topographic information can be obtained from USGS topographic maps. The USGS topographic maps display topographic information as well as the location of roads, lakes, rivers, buildings, and urban land use. Paper or digital maps can be purchased from local vendors or ordered on the USGS Web site: http://store.usgs.gov. Counties often have more detailed topographic information available in a format suitable for use in GIS. Additionally, topographic data suitable for GIS use for the metro area and statewide may be available from MetroGIS www.datafinder.org/index.asp, and the DNR: http://deli.dnr.state.mn.us/data_catalog.html. To acquire detailed topographic data for a site, a local survey may need to be completed. Appendix A contains a general elevation map for Minnesota.

3.1.4. Soils / Surficial Geology

Data on soils can be obtained from county soil surveys completed by the USDA Natural Resources Conservation Service (NRCS). These reports describe each soil type in detail and include maps showing the soil type present at any given location. A list of soil surveys available for Minnesota can be found on the NRCS Web site:

http://soils.usda.gov/survey/printed_surveys/minnesota.html. Soils information could also be obtained by conducting an onsite soil survey, by conducting soil borings, and by evaluating well logs. Other sources of soils information (for example, dominant soil orders as shown in Appendix A) may be found in this list from the Land Management Information Center, http://www.lmic.state.mn.us/chouse/soil.html, from the DNR http://deli.dnr.state.mn.us/data_catalog.html, or from MetroGIS http://www.datafinder.org/index.asp.

3.1.5. Land Cover / Land Use

Land cover and land use information (see example in Appendix A) can be obtained from the local planning agency such as the county or city of interest but may also be available in the sources listed by the Land Management Information Center www.lmic.state.mn.us/chouse/land_use.html, the DNR http://deli.dnr.state.mn.us/data_catalog.html, and MetroGIS www.datafinder.org/index.asp.

3.1.6. Monitoring Data

Monitoring data can be used as model input and for model calibration. Data on lake levels, ground water levels, stream flow, and water quality can be obtained from local monitoring studies or from such agencies as the Department of Natural Resources (DNR) www.dnr.state.mn.us/lakefind/index.html, United States Geologic Survey (USGS) http://www.usgs.gov/state/state.asp?State=MN, Minnesota Pollution Control Agency (MPCA) www.pca.state.mn.us/data/edaWater/index.cfm, and the Metropolitan Council for the Twin Cities metro area www.metrocouncil.org/environment/Riverslakes/.

3.2. Input Guidance

3.2.1. Rainfall Distribution

Storm distribution is a measure of how the intensity of rainfall varies over a given period of time. For example, in a given 24 hour period, a certain amount of rainfall is measured. Rainfall distribution describes where that rain fell over that 24 hour period; that is, whether the precipitation occurred over a one hour period or over the entire 24 hours.

The standard rainfall distribution used for urban areas in Minnesota for sizing and evaluation of BMPs (Chapter 10) is the Natural Resource Conservation Service's (NRCS) recommended SCS Type II rainfall distribution for urban areas. This is a synthetic event, created by the SCS (now the NRCS), of a 24-hour duration rainfall event in which the peak intensity falls in the center of the event (at 12 hours).

The advantage of using the synthetic event is that it is appropriate for determining both peak runoff rate and runoff volume. Drawbacks of using a synthetic event are that they rarely occur in nature and are difficult to explain. Observed precipitation data can be used if analysis with a natural distribution is desired.

Further information regarding rainfall distribution can be found in the Minnesota Department of Transportation's Drainage Manual and in the Hydrology Guide for Minnesota prepared by the Soil Conservation Service (now the NRCS).

3.2.2. Water Quality Event

Small storms are often the focus of water quality analysis because research has shown that pollution migration associated with frequently occurring events accounts for a large percentage of the annual load. This is because of the "first flush" phenomenon of early storm wash-off and the large number of events with frequent return intervals. Rain events between 0.5 inches and 1.5 inches are responsible for about 75% of runoff pollutant discharges (MPCA, 2000).

The rainfall depth corresponding to 90% and 95% of the annual total rainfall depth shows surprising consistency among six stations chosen to represent regional precipitation across the State. The six stations analyzed were Minneapolis/St. Paul International Airport, St. Cloud Airport, Rochester Airport, Cloquet, Itasca, and the Lamberton SW Experiment Station. The rainfall depth which represents 90% and 95% of runoff producing events was 1.09 inches (+/- 0.04 inches) and 1.46 inches (+/- 0.08 inches), respectively. This rainfall depth can be used for water quality analysis throughout the state.

Larger events such as the spring snowmelt, however, can be the single largest water and pollutant loading event in the year. In Minnesota, this spring snowmelt occurs over a comparatively short period of time (i.e., approximately two weeks) in March or April of each year – depending on the region of the state. The large flow volume during this event may be the critical water quality design event in much of the state. See Chapter 2 for a further discussion of snowmelt runoff variation across the state and Chapter 9 for the problems associated with snowmelt.

Technical Bulletin 333: Climate of Minnesota (Kuehnast, 1982), (www.climate.umn.edu/pdf/climate_of_minnesota/comXIII.pdf), shows that the average annual date of snowmelt can be represented by the last date of a 3 inch snow cover. This document also includes figures that allow estimation of the average depth of snowpack at the start of spring snowmelt plus the water content of the snowpack during the month of March (see also Chapter 2).

The estimated infiltration volume can be determined from research in cold climates by Baker (1997), Buttle and Xu (1988), Bengtsson (1981), Dunne and Black (1971), Granger et al. (1984) and Novotny (1988). This research shows that infiltration does in fact occur during a melt at volumes that vary considerably depending upon multiple factors including: moisture content of the snow pack, soil moisture content at the time the soil froze, plowing, sublimation, vegetative cover, soil properties, and other snowpack features. For example, snowmelt investigations by Granger et al. (1984) (see Chapter 2, Figure 2.7) took measurements from 90 sites, located in Saskatchewan Canada, representing a wide range of land use, soil textures, and climatic conditions. From this work, general findings showed that even under conservative conditions (wet soils, ~35% moisture content, at the time of freeze) about 0.4 inches of water infiltrated during the melt period from a one-foot snowpack with a 10% moisture content (1.2 inches of equivalent moisture) in areas with pervious cover. This would not apply to impervious surfaces.

The average snowmelt volume can then be estimated using the equation below (see Chapter 2, Figures 2.6 and 2.7 for input variables):

Other procedures for estimating water quality treatment volume based on annual snow depth are described by the Center for Watershed Protection (CWP) (Caraco and Claytor, 1997), which is available as a free download from the CWP Web page at www.cwp.org/cold-climates.htm.

More snowfall and snowmelt data can be found in the following report sponsored by the Minnesota Department of Transportation: www.climate.umn.edu/snow_fence/Components/SWE/marswe.htm#

For purposes of determining the volume of runoff or snowmelt that should be managed by the site BMPs, designers must make two water quality volume computations: snowmelt and rainfall runoff. The BMP would then be sized for the larger of the two results. Areas with low snowfall will likely find that the rainfall based computations are the larger value, while those areas with greater snowpack will find that snowmelt is larger.

In some cases snowmelt would be selected as the design parameter for computing the volume, whereas other options lead to rainfall as the critical design parameter. More discussion on the various options for selection criteria is contained in Chapter 10, Unified Stormwater System Sizing Criteria.

3.2.3. Extreme Flood Events

Because a spring melt event generates a large volume of water over an extended period of time, evaluation of the snowmelt event for channel protection and over-bank flood protection is generally not as important as the extreme event analysis. This warrants attention because of the possibility that a major melt flooding event could, and sometimes does, happen somewhere in the state.

Conservative design for extreme storms can be driven by either a peak rate or volume event depending upon multiple hydraulic factors. Therefore, depending upon the situation, either the 100-yr, 24-hr rain event or the 100-yr, 10-day snowmelt runoff event can result in more extreme conditions. For this reason, both events should be analyzed. Chapter 9 contains further discussion of the need for special design considerations for snowmelt.

$$\begin{array}{c}\text{Average}\\\text{snowmelt}\\\text{volume}\\\text{(depth/unit area)}\end{array} = \begin{array}{c}\text{Average snow pack}\\\text{depth at the}\\\text{initiation of the}\\\text{snowmelt period}\end{array} \times \begin{array}{c}\text{Typical snow}\\\text{pack water}\\\text{equivalent at}\\\text{time of melt}\end{array} - \begin{array}{c}\text{Estimated infiltration}\\\text{volume likely}\\\text{during a 10-day}\\\text{melt period}\end{array}$$

Protocol for simulation of the 100-yr, 24-hr rainfall event is well established in Minnesota. High water elevations (HWL) and peak discharge rates are computed with storm magnitudes based on TP-40 frequency analysis and the SCS Type II storm distribution.

Protocol has been established for the analysis of HWL and peak discharge resulting from a 7.2 inch 100-yr, 10-day snowmelt runoff event. However, this event has received a considerable amount of criticism. Although not well documented, it is thought that the theoretical snowmelt event was devised by assuming a six inch 100-yr, 24-hr rainfall event occurs during a 10-day melt period in which one foot of snow (with a 10% moisture content) exists at the onset. A typical assumption accompanying the event is that of completely frozen ground (no infiltration) during the melt period for which the result is 100% delivery of volumes. So what do we use? Climate records show that the highest rain event during this common melt period over the past 100+ years was 4.75 inches. An alternative method to consider is to add 4.75 inches of precipitation to the site's snowmelt volume (including infiltration). Designers should compare this to the 7.2 inch, 10-day snowmelt volumes and then determine which is best for the site.

Protocols for computation of extreme snowmelt events should be established as part of a state-wide precipitation study that has been discussed to update TP-40.

3.2.4. Runoff Coefficient

The Rational Method is used to estimate peak runoff rates for very small sites. The simple equation for peak discharge is Q=CiA.Table 8.2 gives runoff coefficient (C) values for use in the Rational Method with, *i* in inches per hour, A in acres, and Q in cfs. The chosen value of C must represent losses to infiltration, detention, and antecedent moisture conditions. Additionally, C varies with the frequency of the rainfall event.

Table 8.2 Runoff Coefficients for 5- to 10-Year Storms* (Source: Haan et al., 1994)

Land Use Description	Runoff Coefficient
Forest*	
< 5% slope	0.30
5% - 10% slope	0.35
> 10% slope	0.50
Open Space	
< 2% slope	0.05 – 0.10
2% - 7% slope	0.10 – 0.15
> 7% slope	0.15 – 0.20
Industrial	0.50 – 0.90
Residential	
Multi-Family	0.40 – 0.75
Single Family	0.30 – 0.50
Impervious Areas	0.7 – 0.95
Row Crops**	
< 5% slope	0.50
5% - 10% slope	0.60
> 10% slope	0.72
Pasture*	
< 5% slope	0.30
5% - 10% slope	0.36
> 10% slope	0.42

*For use in the Rational Method (see Appendix B for use of the Rational Method

**For clay and silt loam soils

What is the Pre-Development Condition?

When a requirement exists to match runoff rate or volume to "pre-development conditions," there is a range of options that could be applied to define land cover conditions. This range goes from pre-settlement, which assumes land is in an undeveloped condition, to the land use condition immediately prior to the project being considered, which assumes some level of disturbance in the natural landscape has already occurred. Interpretations of this variation from Scott County, Project NEMO, Dane County (WI), and the USDA-NRCS were used to lay out the range of approaches that local units can use when applying this criterion. Please note that selection of a pre-development definition should occur only after an evaluation of the hydrologic implications of the choice is performed.

Pre-Settlement Conditions

The most conservative assumption for pre-development conditions is the assumption that the land has undergone essentially no change since before settlement. In this case, a meadow or woodland in good condition is commonly used to portray a "natural" condition. Table 8.3 shows the curve numbers used when this situation is applied using TR-55. Similar hydrologic characteristics would be applied when using other models

Table 8.3: Curve Numbers Used in Pre-Settlement Condition

	Runoff Curve Number*	
Hydrologic Soil Group (HSG)	**Meadow**	**Woods**
A	30	20
B	58	55
C	71	70
D	78	77

*** Curve numbers from USDA-NRCS, Technical Release 55**

Conditions Immediately Preceding Development

On the other end of the pre-development definition is the assumption that land disturbance has previously occurred with the land use in place at project initiation. This is the definition used under most circumstances by the MPCA in the Construction General Permit (CGP). Under this scenario, runoff assumptions after construction need to match those of the land use prior to the development using matching curve numbers or runoff coefficients. The new project could possibly improve runoff conditions, if the prior land use did not accommodate any runoff management. That is, implementation of good runoff management to an area that had previously developed without it would likely reduce total runoff amount compared to existing development. Note that the MPCA could alter its definition of pre-development under certain circumstances, such as a TMDL established load limit.

NRCS (TR-55) notes that heavily disturbed sites, including agricultural areas, curve numbers should be selected from the "Poor Condition" subset under the appropriate land use to account for common factors that affect infiltration and runoff. Lightly disturbed areas require no modification. Where practices have been implemented to restore soil structure, no permeability class modification is recommended.

Table 8.4 Curve Numbers for Antecedent Moisture Condition II (Source: NRCS)

Land Use Description	Hydrologic Soil Group			
	A	B	C	D
Meadow				
Good condition	30	58	71	78
Forest				
Poor	45	66	77	83
Fair	36	60	73	79
Good	30	55	70	77
Open Space				
Poor	68	79	86	89
Fair	49	69	79	84
Good	39	61	74	80
Commercial				
85% impervious	89	92	94	95
Industrial				
72% impervious	81	88	91	93
Residential				
1/8 ac lots (65% impervious)	77	85	90	92
1/4 ac lots (38% impervious)	61	75	83	87
1/2 ac lots (25% impervious)	54	70	80	85
1 acre lots (20% impervious)	51	68	79	84
Impervious Areas	98	98	98	98
Roads (including right of way)				
Paved	83	89	92	93
Gravel	76	85	89	91
Dirt	72	82	87	89
Row Crops				
Straight row – Good	67	78	85	89
Contoured row – Good	65	75	82	86
Pasture				
Good	39	61	74	80
Open Water	99	99	99	99

3.2.5. Curve Numbers

Curve numbers are used in the SCS Method to represent the runoff expected after initial abstractions and infiltration into the soil. Curve numbers are based on land use and hydrologic soil group. The SCS (now the NRCS) developed tables with curve numbers appropriate for urban, agricultural, arid and semiarid rangeland, and undisturbed land uses. Hydrologic soil group can be determined from soil surveys.

Curve number tables are published in TR-55: Urban Hydrology for Small Watersheds (ftp://ftp.wcc.nrcs.usda.gov/downloads/hydrology_hydraulics/tr55/tr55.pdf) but are also available in textbooks and within modeling software.

Curve numbers vary for smaller storms (see discussion in SLAMM documentation: http://www.unix.eng.ua.edu/~rpitt/SLAMMDETPOND/WinSlamm/Ch2/Ch2.html.) A short summary of some more commonly used curve numbers is given in Table 8.4.

The selection of appropriate curve numbers is of great importance when using the SCS Method. Sizing of facilities and comparisons of existing or pre-development conditions to proposed developed conditions can depend highly on the selected curve numbers. MPCA uses the land cover in place immediately before the proposed project as the "pre-development condition". Many other regulators use a more natural condition to reflect change from pre-European settlement times.(See box on previous page). The hydrologic soil group of the native soils should be used for pre-development conditions, but developed conditions may alter the soil condition by compaction, fill, or soil amendments. In the more conservative, natural definition of pre-development condition, land use would be meadow or woods in good condition as appropriate to the natural state of the site. Chapter 10 contains further discussion of the option for defining pre-development conditions. Special care should be taken to identify areas of soil group D and areas of open water as these areas have high levels of runoff. Care must also be taken when selecting curve numbers for agricultural land as its use can change considerably annually and even over the course of a season.

A. Composite Curve Numbers

According to the NRCS (TR-55, 1986), curve numbers describe average conditions for certain land uses. Urban area curve numbers are a composite of grass areas (assumed to be pasture in good condition) and directly connected impervious areas. TR-55 guidance documentation recommends that curve numbers be adjusted under certain conditions:

- When the percentage of impervious cover differs from the land use contained in curve number tables.
- When the impervious area is unconnected.
- When weighted curve number is less than 40.
- When computing snowmelt on frozen ground.

NRCS advises that the curve number procedure is less accurate when runoff is less than ½ inch. Other procedures should be followed to check runoff from these smaller events. One technique could be to compute runoff from pervious and impervious areas separately, with unique rather than composite curve numbers.

Specific guidance is available in NRCS Technical Release 55 (available at NRCS National Water and Climate Center).

B. Antecedent Moisture Conditions

Antecedent moisture conditions (AMC) describe the moisture already present in the soil at the time of the rain event. AMC level I represents dry conditions, level II represents normal conditions, and level III represents wet conditions. Normal conditions are defined as 1.4 to 2.1 inches of rainfall in the growing season in the five days preceding the event of interest. Most evaluations of expected future site conditions use the curve numbers appropriate to AMC II. However, if the specific conditions of interest are expected to differ, curve numbers appropriate to AMC I or III should be used.

Modeling Recommendations

Pre-development conditions land use can vary from land use composed of meadow or woods in good condition as appropriate to the natural state of the site to the condition of the site immediately preceding development.

Most evaluations of expected future site conditions should use the curve numbers appropriate to AMC II.

Event mean concentrations can range by an order of magnitude for a given land use, therefore, it is best to have local data for calibration purposes.

Table 8.6 Infiltration Rates Observed in Infiltration Practices Operating in Minnesota

Source of Data	Range of Infiltration Rates [inches/hour]	Number of Monitoring Sites	Brief Description of Site	Monitoring Dates
South Washington Watershed District	0.14 – 3.10*	1	Monitoring data collected at regional basin CD-P85.*	1999 - 2005
South Washington Watershed District	0.03 – 0.6	4	Monitoring data collected at 4 natural infiltration basins. Soils in the basins consist of silt loams underlain by sands and gravel interspersed with clayey-silty sediments.	1999 - 2005
South Washington Watershed District	0.02 – 5.0	1	Infiltration trench located at the Math and Science Academy in Woodbury, MN. In order to intersect more permeable material, trench is 15 feet deep for a portion of the practice. Underlying material is variable: till and sand/gravelly sand. Trench receives pretreatment of stormwater prior to infiltration.	1999 - 2005
South Washington Watershed District	0.02 – 3.02	1	Infiltration trench located in regional basin CD-P85. These trenches are an average of 13 feet deep. Underlying material is sand and gravelly sand.	1999 - 2005
Rice Creek Watershed District	0.03 – 0.59	4	Monitoring data collected at 3 rain gardens and an infiltration island located at Hugo City Hall. Soils in the basins consist of silty fine sand with a shallow depth to the water table. Trench receives significant pretreatment of stormwater prior to infiltration.	2002 - 2003
Brown's Creek Watershed District	0.01 – 0.20	2	Monitoring data collected at two infiltration basins. Soils in the basins consist of silty sand and sandy silt interspersed with clayey sandy silt.	2000 - 2005
Field's of St. Croix, Lake Elmo, MN	0.02 - 0.14	3	Monitoring data collected at 3 infiltration basins located in a residential development. Soils in the basins consist of sandy loam and silt loam (HSG B).	2001 - 2003
Bradshaw Development, Stillwater, MN	0.26 – 0.28	1	Monitoring data collected in one infiltration basin located in a commercial development. Soils in the basin consist of silty sand.	2005

*The high end of this rage (3.1 iph) is not representative of typical rates for similar soil types. This facility is periodically subject to 25 foot depths of water, is underlain by more than 100 feet of pure sand and gravel without any confining beds and the depth to the water table is greater than 50 feet below the surface. In addition, two infiltration enhancement projects have been constructed in the bottom of the facility to promote infiltration: five dry wells and two infiltration trenches have been operating in CD-P85 at various periods of the monitoring program.

3.2.6. Infiltration Rates

Infiltration is the process of water entering the soil matrix. The rate of infiltration depends on soil properties, vegetation, and the slope of the surface, among other factors. Discussions of infiltration often include a discussion of hydraulic conductivity. Hydraulic conductivity is a measure of ease with which a fluid flows through the soil, but it is not the infiltration rate. The infiltration rate can be determined using the hydraulic conductivity through the use of the Green-Ampt equation. The Green-Ampt equation relates the infiltration rate as it changes over time to the hydraulic conductivity, the pressure head, the effective porosity, and the total porosity. Typical values used in the Green-Ampt equation can be found in Rawls, et al. (1983).

A simple estimate of infiltration rates can be made based on the hydrologic soil group or soil texture (Table 8.5). These infiltration rates represent the long-term infiltration capacity of a constructed infiltration practice and are not meant to exhibit the capacity of the soils in the natural state. The recommended design infiltration rates fit within the range of infiltration rates observed in infiltration practices operating in Minnesota (Table 8.6). The length of time a practice has been in operation, the location within the basin, the type of practice, localized soil conditions and observed hydraulic conditions all affect the infiltration rate measured at a given time and a given location within a practice. The range of rates summarized in Table 8.6 reflects the variation in infiltration rate based on these types of factors. Information on measuring infiltration rates and the use of the numbers presented in Table 8.5 can be found in the infiltration section in Chapter 12 of this manual.

3.2.7. Event Mean Concentrations

Event mean concentrations (EMCs) of a particular pollutant (i.e. total phosphorus, total suspended solids) are the expected concentration of that pollutant in a runoff event. Along with runoff volume, EMCs can be used to calculate the total load of a pollutant from a specific period of time. EMCs are frequently based on land use and land cover, with different predicted pollutant concentrations based on the land use and/or land cover of the modeled area.

Table 8.7 lists EMCs for total phosphorus (TP) that were reported in Pitt et al. (2004). EMCs can range by an order of magnitude for a given land use, an it is therefore best to have site-specific or comparable local data for calibration purposes. The EMCs in the Pitt et al. study were from the National Stormwater Quality Database (NQSD, Version 1.1). Note also that EMCs are concentration data, which are only part of the overall loading equation. Although some land uses might have a high EMC, for example open space at 0.27-0.31 mg/l, little runoff occurs from this land so overall phosphorus loading is low.

Table 8.7 Typical Event Mean Concentrations for Total Phosphorus

Land Cover/Land Use	Total Phosphorus (mg/L)
Cropland[1]	0.32
Forest/Shrub/ Grassland[1]	0.04
Open Water[1]	0.01
Wetlands[1]	0.01-0.04*
Freeways[2]	0.25
Commercial[1,2]	0.22
Farmsteads[1]	0.46
Industrial[1,2]	0.26
Residential[2]	0.30
Multi-Family Residential[1,2]	0.27-0.32
Park and Recreation[1]	0.04
Open Space[1,2]	0.31
Public/Semi Public (Institutional)[1,2]	0.18

[1] Minnehaha Creek Watershed District, 2003

[2] Robert Pitt *et al.*, 2004

* Average for large wetlands and wetland complexes. Individual wetlands should be monitored to determine source/sink behavior.

Table 12.BIO.8 Design Infiltration Rates

Hydrologic Soil Group	Soil Textures*	Corresponding Unified Soil Classification**	Infiltration Rate [inches/hour]
A	Gravel, sand, sandy gravel, silty gravel, loamy sand, sandy loam	**GW** – Well-graded gravel or well-graded gravel with sand **GP** – Poorly graded gravel or poorly graded gravel with sand	1.63
		GM – Silty gravel or silty gravel with sand **SW** – Well-graded sand or well-graded sand with gravel **SP** – Poorly graded sand or poorly graded sand with gravel	0.8
B	Loam, silt loam	**SM** – Silty sand or silty sand with gravel	0.6
		ML – Silt **OL** – Organic silt or organic silt with sand or gravel or gravelly organic silt	0.3
C	Sandy clay loam	**GC** – Clayey gravel or clayey gravel with sand **SC** – Clayey sand or clayey sand with gravel	0.2
D	Clay, clay loam, silty clay loam, sandy clay, silty clay	**CL** – Lean clay or lean clay with sand or gravel or gravelly lean clay **CH** – Fat clay or fat clay with sand or gravel or gravelly fat clay **OH** – Organic clay or organic clay with sand or gravel or gravelly organic clay MH – Elastic silt or elastic silt with sand or gravel	< 0.2

Source: Thirty guidance manuals and many other stormwater references were reviewed to compile recommended infiltration rates. All of these sources use the following studies as the basis for their recommended infiltration rates: Rawls, Brakensiek and Saxton (1982); Rawls, Gimenez and Grossman (1998); Bouwer and Rice (1984); and Urban Hydrology for Small Watersheds (NRCS). The rates presented in this infiltration table use the information compiled from these sources as well as eight years of infiltration rates collected in various infiltration practices located in the South Washington Watershed District.

*U.S. Department of Agriculture, Natural Resources Conservation Service, 2005. National Soil Survey Handbook, title 430-VI. (Online) Available: http://soils.usda.gov/technical/handbook/.

**ASTM standard D2487-00 Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System).

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